Clumping in Hot Star Winds
W.-R. Hamann, A. Feldmeier & L. Oskinova, eds.
Potsdam: Univ.-Verl., 2007
URN: http://nbn-resolving.de/urn:nbn:de:kobv:517-opus-13981

The influence of clumping on predicted O star wind parameters

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We study the influence of clumping on the predicted wind structure of O-type stars. For this purpose we artificially include clumping into our stationary wind models. When the clumps are assumed to be optically thin, the radiative line force increases compared to corresponding unclumped models, with a similar effect on either the mass-loss rate or the terminal velocity (depending on the onset of clumping). Optically thick clumps, alternatively, might be able to decrease the radiative force.

1 Introduction

Theoretical models of hot star winds led to the conclusion that mass-loss has a significant impact on the stellar evolution in the upper HRD. This conclusion was supported by a relatively good agreement between these models and observational data.

However, both theoretical predictions and observational values were derived, in a first approximation, by assuming the stellar wind to be a smooth, spherically symmetric outflow. This picture might be inadequate due to the existence of a strong instability related to radiative line driving (see Feldmeier, this volume, and references therein). The influence of corresponding spatially inhomogeneous wind structures ("clumps") on the basic wind properties (i.e., mass-loss rate and velocity field) and the emergent spectrum was believed to be insignificant.

This changed with the application of NLTE models that were able to account for the influence of clumping on hot star wind spectra. The reason that the effect of clumping is not immediately apparent in the wind spectra is that most diagnostical features depend on the *product* $\sqrt{C_\mathrm{c}}\dot{M}$, where the "clumping factor" $C_\mathrm{c} \geq 1$ relates the density inside the clump ρ^+ with the mean wind density $\langle\rho\rangle$,

$$\rho^+ = C_\mathrm{c}\langle\rho\rangle. \tag{1}$$

Consequently, spectra from winds with a large clumping factor but small mass-loss rate can mimic those from winds with weak clumping but large mass-loss rate. If $C_\mathrm{c} > 1$, then the mass-loss rates derived from such diagnostics are overestimated by a factor of $\sqrt{C_\mathrm{c}}$. Fortunately, some spectral properties may be used to break this degeneracy, and to "observationally" estimate the value of C_c. For example, Martins et al. (2005b) derived clumping factors of 10 and 100 for studied Galactic O-stars, implying a decrease of the estimated mass-loss rate by factors of 3 and 10 (see also Bouret, this volume, and Puls et al., this volume, and references therein).

Thus, if the actual mass-loss rates of hot stars are really lower than assumed before, then there is a significant discrepancy between the observations and theory. The reason for this discrepancy is not yet known. A possibility might be that clumping may shift the ionization balance in such a way that the final radiative force is lower, resulting in lower mass-loss rates. To test this possibility we have included clumping into our wind models and studied its influence on the basic wind properties of hot stars.

2 Model stars

The wind models are calculated for O-type stellar parameters based on the recent calibrations by Martins et al. (2005a, see also Fig. 1).

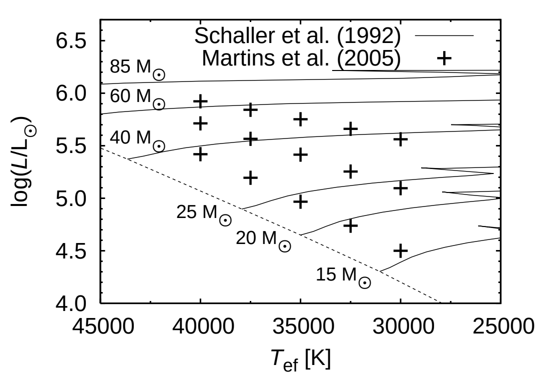

Figure 1: Parameters of studied stars in the HR diagram. Overplotted are the evolutionary tracks from Schaller et al. (1992).

3 Wind models

For our study we used the spherically symmetric, stationary wind models developed by Krtička & Kubát (2004). These models solve the equations of statistical equilibrium together with the equations of radiative transfer. The calculated occupation numbers are used to derive the radiative force (in the Sobolev approximation) and the radiative heating/cooling terms. This enables us to obtain the radial stratification of velocity, density and temperature in the wind and finally to predict the wind mass-loss rate $\dot{M}$ and terminal velocity v_∞. For the studied O-stars, $\dot{M}$ derived from our models depends on the stellar luminosity L and the effective temperature T_{eff} on average as

$$\left(\frac{\dot{M}}{1\,\mathrm{M}_\odot\,\mathrm{year}^{-1}}\right) = 8.13\times10^{-7}\left(\frac{L_*}{3\times10^5\,\mathrm{L}_\odot}\right)^{2.05} \times\left(\frac{T_{\mathrm{eff}}}{3.5\times10^4\,\mathrm{K}}\right)^{3.78}. \quad (2)$$

The advantage of our models is the self-consistent solution of the momentum equation, though the radiative transfer is treated in a simplified way.

4 Optically thin clumps

The assumption of optically thin clumps is widely used for studying the influence of clumping on the wind spectra (e.g., Martins et al. 2005b, Puls et al, this volume).

To include optically thin clumps into our models we modified the equations of statistical equilibrium, by using an electron density $\rho_{\mathrm{e}}^+ = C_{\mathrm{c}}\langle\rho_{\mathrm{e}}\rangle$, opacity $\langle\chi\rangle = \chi^+/C_{\mathrm{c}}$, and emissivity $\langle\eta\rangle = \eta^+/C_{\mathrm{c}}$. The superscript + denotes values inside the (homogeneous) clumps and the quantities inside brackets corresponding volume averages.

4.1 Influence of clumping

To investigate the influence of clumping on the stellar wind we have calculated a wind model of an O-type giant at $T_{\mathrm{eff}} = 35\,000\,\mathrm{K}$, assuming the wind to be smooth ($C_{\mathrm{c}} = 1$) close to the star ($r < 2R_*$), and to be clumped ($C_{\mathrm{c}} = 10$) in the outer regions ($r > 2R_*$, see Figs. 2, 3).

The presence of clumping leads to an increase of the electron density inside the clumps. Consequently, the recombination rates become higher and the wind less ionized (see Fig. 2). Since lower ions are able to accelerate the stellar wind more efficiently than the higher ones (due to a larger number of driving lines), the radiative force increases, which, in our case, leads to an increase in wind velocity (see Fig. 3).

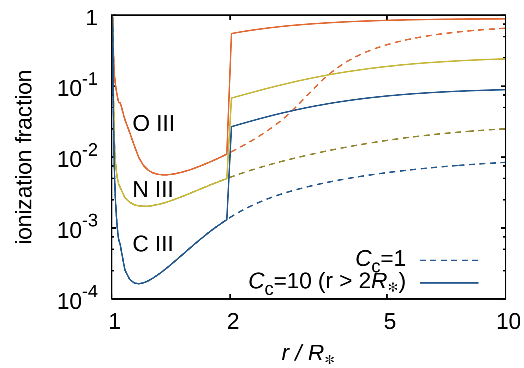

Figure 2: Influence of clumping on the ionization fractions of selected ions.

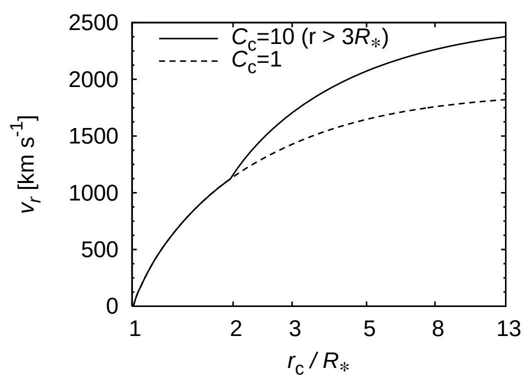

Figure 3: Influence of clumping on the wind velocity.

4.2 Radially constant clumping factor

The influence of clumping on the wind parameters depends on the radial onset of clumping. If clumping starts above the critical point (below which the mass-loss rate is determined), then the terminal velocity increases (see Fig. 3). On the other hand, if clumping starts below the critical point, then the wind mass-loss rate becomes larger.

Table 1: Average increase of $\dot{M}$ for constant C_{c}

C_{c}	1	3.16	10	31.6	100
$\dot{M}(C_{\mathrm{c}})/\dot{M}(C_{\mathrm{c}}=1)$	1	1.48	2.15	3.17	4.57

In case of radially constant clumping, the mass-loss rate increases significantly, and the predicted

wind-momentum rate is much higher than for a smooth wind at same parameters (see Fig. 4).

5 Clumps larger than L_{Sob}

Individual clumps may be larger than the Sobolev length L_{Sob}. Assuming the velocity gradient inside the clumps to be the same as in the corresponding smooth wind, we account for clumps being larger than L_{Sob} by using the same modifications as in the case of optically thin clumps, but additionally increasing the Sobolev optical depth by C_{c}, and decreasing the radiative force per unit of volume by a factor of C_{c}.

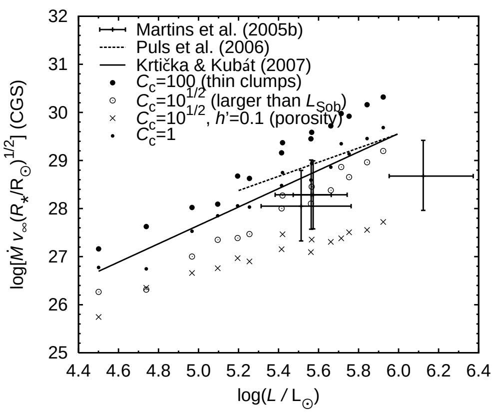

Figure 4: Influence of wind inhomogeneities on the modified wind-momentum rate.

The inclusion of clumps larger than L_{Sob} into our wind models leads to a decrease of the radiative force. Thus, and for radially constant C_{c}, the mass-loss rate decreases significantly (Fig. 4).

6 Influence of porosity

Wind porosity (Owocki et al. 2004) can be introduced into the wind models by additional decreasing the continuum opacity, $\chi_{\mathrm{eff}} = \frac{\langle\chi\rangle}{1+rh'\langle\chi\rangle}$, where $h'r$ is the porosity length. The continuum emissivity has to be modified by the same amount.

This effect leads to a significant increase of the wind ionization. Thus, porosity leads to a decrease of the radiative force, and also the mass-loss rate may decrease if the wind is porous below the critical point (see Fig. 4 for the results for radially constant C_{c} and h').

7 Discussion

Our results are in agreement with those derived from a similar investigation conducted by de Koter & Muijres (this volume): Indeed, *wind inhomogeneities influence the predicted wind parameters*. An approach which roughly corresponds to the results of time-dependent simulations (i.e., clumps which are optically thin at most frequencies, “starting” above the critical point) does not improve the agreement between theory and observations. Clumps assumed to be larger than the Sobolev length (and starting below the critical point) may provide a better agreement between theory and observations, both in terms of mass-loss rates (Fig. 4) and P V ionization fractions (Fig. 5). Note, however, that the approach chosen by us strongly contrasts an important aspect of time-dependent simulations, namely that the velocity gradient inside the clumps is predicted to be much shallower than that of a corresponding smooth wind. This problem will be considered in a follow-up investigation.

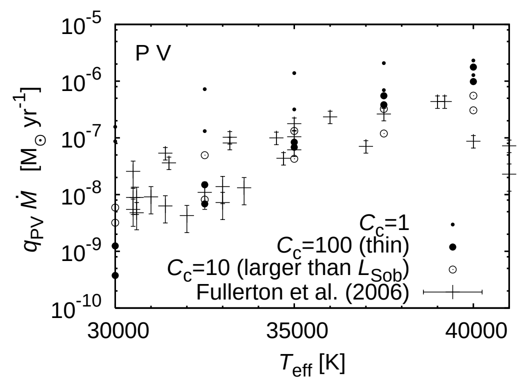

Figure 5: Influence of different types of wind inhomogeneities on the P V ionization.

Acknowledgements This research was supported by grants GA ČR 205/07/0031 and GA AV ČR B301630501.

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